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Use of a high density, low temperature, bubble column for thermally efficient water sterilization

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ABSTRACT

An unusual property of salt water, that is its ability to inhibit air bubble coalescence, has been used as the basis for a new method of water sterilization. In this process, high-temperature gas is passed through a porous sinter into a contaminated aqueous solution containing at least 0.15 M NaCl, to prevent bubble coalescence. It is found that even at high gas temperatures, the presence of salt still inhibits bubble coalescence and hence high bubble volume fractions of small bubbles can be attained, which is shown to improve the efficiency of the sterilization process. It has been established that the continuous flow of hot (dry) gases, even at 150 °C, only heat the aqueous solution to about 45 °C, which is an ideal temperature for bacterial colony growth in typical contaminated water. Hence, it has been established that sterilization occurs due to the transient collision of biological species with the hot gas bubbles. This new method has a significantly improved energy efficiency over the standard process of sterilization of boiling the contaminated water for 5–30 min, as typically recommended.

Keywords: Thermal sterilization; Non-boiling sterilization; Bubble coalescence; High-density bubble column

1. Introduction

The current work was aimed at developing a novel process to improve the energy efficiency of water sterilization without the need for boiling. This can be achieved using a remarkable but still unexplained property of salt water. Russian mineral flotation engineers in the 1930s discovered that adding salt to a flotation chamber significantly improved its efficiency because finer bubbles were produced [1]. This occurs because the bubbles formed at a porous sinter or frit do not coalesce above a certain salt concentration. Although there is still no clear explanation for this phenomenon, it has been well studied [2–5]. It turns out that some salts inhibit bubble coalescence and some have no effect. Common salt does cause inhibition and this reaches a maximum effect above about 0.17 M, which surprisingly happens to be the salt level in the human body. It has been suggested that this is not by coincidence, but that this salt level is important because it protects our body from decompression sickness, even at atmospheric pressure [2,3]. Further increases in the salt level have no greater effect. Salt levels in sea water vary but are typically around 0.55 M. The foaming of waves on the sea shore is also due to this effect of salt. This strange phenomenon means that it is possible to produce a high volume

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fraction of bubbles in a column of salt water. Warming the salt solution to about 50°C has only a slight effect and actually reduces bubble coalescence still further [3].

During bubbling, the water column cools when the air humidity is less than saturated. The rate of cooling depends upon the gas temperature, gas flow rate, initial column temperature, and the volume of water in the column [6]. The cooling rate slows and eventually reaches a steady state equilibrium temperature; when the heat from the gas entering the system is precisely balanced by the heat required to vaporize water to saturate the incoming dry gas [6].

The final steady state temperature attained by a thermally insulated bubble column, cooled by evaporative cooling, can be calculated directly from the temperature of the inlet gas, its heat capacity, and the heat of vaporization of water, ΔH_v, at that steady state temperature, and the saturated water vapor density in air at that temperature (ρ_v in mol/m^3). Fortunately, the heat capacity (C_p) of a gas such as nitrogen (or air) is quite constant over a fairly wide temperature range, of 0–100°C. It has a value of 1.040 J/gK, at a constant pressure of 1 atm [7]. The saturated water vapor density, at equilibrium, can be obtained directly from its vapor pressure using the ideal gas equation, since vapor density is proportional to vapor pressure.

When the bubble column has reached its steady state temperature (T_e), each new bubble entering the column must, on average, supply precisely the amount of thermal energy (and contraction work) required to evaporate water to saturate the bubble, at that temperature [6]. The amount of heat (and work) supplied by each gas bubble, as it cools by ΔT, is given by the difference between the inlet gas temperature (T_i) and the temperature of the gas as it exits the system (T_o) multiplied by the specific heat of the gas, at constant pressure, in units of J/m^{3}K. In the ideal situation T_o will be equal to the steady state temperature of the column (T_e). There is one other work term to be included in the energy balance and this is the work supplied to the column by the decrease in pressure of the gas as it passes through the column. This work is simply given by pressure difference (ΔP) between the point just before the gas enters the sinter and atmospheric pressure, into which it is released as the gas leaves the column. In the experiments reported here, this pressure was measured, whilst gas was flowing through the column, by using a side tube filled with water. At steady-state equilibrium, the energy balance, in Joules per m^3 of gas leaving the top of the column, is given by the equation:

$$[\Delta T \times C_p(T_e)] + \Delta P = \rho^v(T_e) \times \Delta H_v(T_e) \times (\text{in units of J/m}^3) \quad (1)$$

It should be noted that in this balance of energies, the work done by the reduction in volume of the gas, on cooling, is taken into account in the C_p term and the work done by the expansion of the bubbles, on absorbing water vapor, is included in the ΔH_v term. Note also that since specific heat values for gases are typically tabulated in units of J/gK, these must be converted into the specific heat per unit volume of gas (leaving the top of the column) at the equilibrium temperature of the column, that is, in units of J/m^{3}K.

Eq. (1) shows that the steady-state temperature (T_e) of the column is determined by the gas inlet temperature, (T_i), and not by its flow rate, assuming perfect thermal insulation of the bubble column. That is, the inlet gas temperature can be directly calculated for any water column from the equilibrium temperature and the hydrostatic pressure drop across the column. The gas flow rate only determines how quickly the column reaches equilibrium. Calculated results, using Eq. (1), for a water column bubbled with nitrogen gas at different inlet temperatures are given in Fig. 1. These results clearly demonstrate the evaporative cooling effect of a bubble column.

A high surface area, gas/water interface can be continuously produced by pumping gas through a 40–100 μm pore size glass sinter to produce a continuous stream of bubbles within a column filled with water. When the water is replaced with aqueous NaCl solution of about 0.15 M, or more, finer bubbles are produced (of about 1–3 mm diameter) giving an opaque column, because the presence of salt inhibits bubble

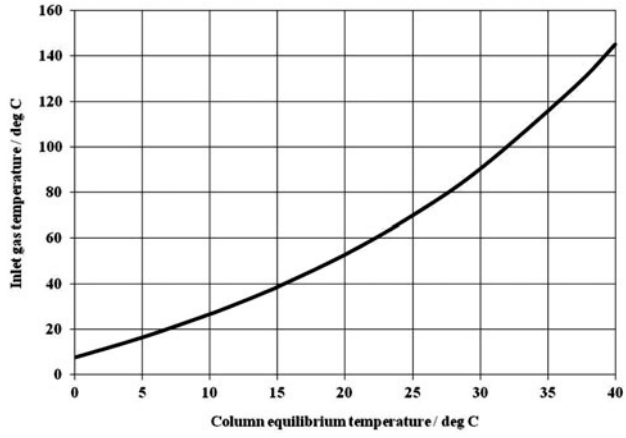

Fig. 1. Bubble column equilibrium temperatures calculated using Eq. (1) for nitrogen gas in aqueous solution for a range of inlet gas temperatures.

coalescence [2,3]. These gas bubbles actually rise at a limited rate of between about 15 and 35 cm/s in quiescent water because they undergo shape oscillations which dampen their rise rate [8,9]. These oscillations also accelerate the rate of transfer of water vapor into the bubbles and so enhance the rate of vapor collection. Equilibrium vapor pressure within the bubbles is, therefore, attained quite quickly, within a few tenths of a second [8]. Hence, the bubbles will reach saturated vapor pressure within a travel distance of about 5–10 cm and so a simple bubble column can be used to efficiently collect water vapor. This process for these size bubbles also indicates that there should be an efficient transfer of heat from a hot bubble to the surrounding solution.

The efficiency of this heat transfer process has been applied in the current study, where hot gas bubbles (up to 150˚C) have been passed through a sinter into a water column and its effect on sterilization examined. The degree of sterilization was determined using natural lake water heavily contaminated with coliforms from waterfowl and land run-off. These coliform counts were used to measure the degree of sterilization obtained using hot gas bubbling under a range of conditions but in all cases where the column solution temperature never exceeded the optimum growing temperature for the coliforms.

2. Methods

2.1. Sterilization

A high surface area air/water interface was continuously produced by pumping air through a 40–100 μm pore size glass sinter into a 115 mm diameter glass column of height 250 mm. Bubbling at a modest rate into a column filled with salt water at about 0.15 M NaCl produces fine bubbles, in the approximate range of 1–3 mm diameter, and an opaque column, compared with the relatively clear column produced in drinking water, which produces larger bubbles [2,3]. Use of salt water in the column, therefore, significantly improves the efficiency of thermal transport when gases are at a temperature significantly above the solution temperature of the column. The apparatus used to control the temperature of the air flowing into the glass sinter column is shown in Fig. 2.

The (dry) air temperature was varied using a Tempco low-density air heater with a thermocouple temperature monitor and an AC Variac electrical supply. The actual temperature of the air flowing into the solution was measured using a thermocouple, with no solution present, just above the inside center of the sinter. The air was pumped using a HIBLOW air pump with a BOC gas flow meter. The temperature of the column solution was continuously monitored using a thermocouple positioned within the column solution. The high-temperature air flow, of up to 300˚C, needed to produce a 150˚C air temperature just above the glass sinter necessitated the use of steel and brass connectors sealed using high-temperature perfluoroelastomer "O" rings, for the downstream output from the hot gas heater.

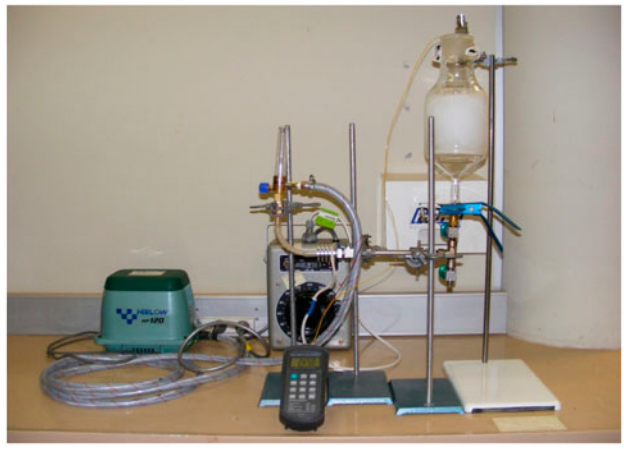

Fig. 2. Photograph of the bubble column sterilization apparatus.

The actual heated gas flow rate into the column can be estimated using the ideal gas equation from the BOC gas flow rate measured just prior to the gas heater. For example, the flow rate at 150˚C is given by the simple relation: gas flow rate through sinter = air inlet flow rate $\times (T_{\text{sinter gas}}/T_{\text{room}})$ with T in Kelvin, which corresponds to a flow rate into the sinter of about 1.44 × the room temperature gas inlet flow rate. Most of the experiments reported here used an inlet (room temperature) gas flow rate of 23 L/min which corresponds to a flow rate of about 33 L/min of 150˚C gas into the sinter. However, as will be demonstrated later, the gas bubbles rapidly cool within the bubble column due to water evaporation and hence only the room temperature gas inlet flow rates are reported here.

The size range of the bubbles produced in the column was obtained from photographs taken with a fast shutter (1/4,000 s) DSLR camera. Since the bubbles in the size range studied travel at about 25 cm/s [8], bubbles of about 1 mm diameter would only travel about 6% of their diameter at this speed.

The full spectrum of fine particles contained in the heavily contaminated raw lake water samples used in this study were evaluated from turbidity measurements obtained using a Hach 2100 AN Turbidimeter.

2.2. Fecal coliform: membrane filtration method

Coliforms are normal inhabitants of the digestive tracts of animals, including human, and are found in their wastes and in soil. They can be used as an indicator of many other organisms present in contaminated water and, in addition, the concentrations of pathogens are usually quite small. On the other hand, coliforms are not specific indicators of fecal pollution and the presence of *E. coli* (thermophilic coliforms) is proved to be the most appropriate group of coliforms to indicate fecal pollution from warm-blooded animals. According to the WHO standard, potable water should be free of coliform organisms [10]. In this study, we have selectively used coliform numbers as the indicator organism to measure the degree of sterilization in naturally contaminated water.

All of the water samples used in this sterilization study were obtained from the shore of a natural lake in a region heavily populated with a wide variety of waterfowl. The sample area was also susceptible to natural land run-off and the water samples were taken at the height of summertime in Canberra. The membrane filtration technique was used to measure the quantity of fecal coliform bacteria present in these water samples, before and after sterilization.

The water samples were filtered through sterile cellulose nitrate 47 mm filters with 0.45 μm pore size. The filters were then placed in petri dishes containing M-FC Agar broth with rosolic acid and incubated for a period of 24 h at 37˚C. The M-FC Agar suppresses the growth of non-coliform bacteria and aniline blue along with rosolic acid forms the indicator system of the media [11]. Coliforms form blue colonies and non-coliforms form grey-colored colonies on M-FC Agar.

Sterilized forceps were used to carefully position each filter membrane onto the filter holder and a small amount of sterile water was poured onto the filter to help seat it. In each case, 10 mL of the water sample was filtered using a vacuum filtration system.

Sterilized forceps were then used to carefully remove the filter which was then placed grid side up on the agar in a petri dish. Care was taken to remove air pockets between the filter and agar. The petri dishes were then covered, stacked upside down and incubated for 24 h in a controlled 37˚C incubator.

Following incubation, the petri dishes were removed from the incubator and each dish was either counted, observed, or photographed for fecal coliform colonies. It is important to note that each bluish spot should be counted as at least one fecal coliform colony. Cream, gray-colored, and colonies of other colors are not fecal coliform colonies, so they have not been included in the count.

Fig. 3. Photograph of a bubble column containing pure water with an inlet gas flow rate (RT) of 23 L/min at an inlet temperature of 147˚C. The column solution temperature was about 45˚C.

3. Results and discussion

The air bubbles formed within the bubble column filled with distilled water at room temperature and with an air inlet temperature of up to 150˚C were large, up to a cm in diameter (see Fig. 3). However, addition of 0.15 M NaCl (or higher concentrations) produced much finer bubbles (1–3 mm diameter) at room temperature, as observed earlier, and even with high air inlet temperatures, up to 150˚C, as shown in Fig. 4. The only difference between Figs. 3 and 4 is the addition of 0.5 M NaCl.

Fig. 4. Photograph of a bubble column containing of 0.5 M NaCl solution with an inlet gas flow rate (RT) of 23 L/min at an inlet temperature of 147˚C. The column solution temperature was about 45˚C.

Photographs of the air bubbles produced in the bubble column using a high temperature (150˚C) air flow in 0.5 M salt solution indicated a bubble size distribution ranging from 0.5 to 2.5 mm diameter. The air flow was continued for 20–30 min to allow the column solution temperature to reach equilibrium. For the 0.5 M solution, the steady state temperature was about 45˚C, which is consistent with the predictions of the evaporative cooling model discussed earlier (see Fig. 1). Comparison between Figs. 3 and 4 clearly shows that the effect of salt in inhibiting bubble coalescence is maintained even though the gas inlet temperature is high (about 150˚C). This is as surprising as the earlier reported results [3] which showed that raising the column solution temperature to 60˚C actually enhances the inhibition effect. The film drainage time, such as that between two colliding bubbles, is proportional to the square root of the viscosity of the solution [12]. Hence, it might be expected that coalescence would be enhanced at higher solution and gas temperatures, since the viscosity of the solution is reduced but this seems not to be the case.

Unfortunately, there is still no proper explanation for the effects of salt on bubble coalescence inhibition. Indeed, at first sight, adding salt would be expected to enhance coalescence because this increases the surface tension of water and hence the bubble energy. Also, adding salt should effectively screen out any repulsive electrostatic force between charged bubbles [13]. Short range van der Waals forces between bubbles will be attractive [13], as will any long range hydrophobic forces [14,15].

Although the explanation for this effect is still illusive, it seems likely that the cause is related to dynamic effects, since, when two individual bubbles are forced together, they will eventually always coalesce, even in water at high salt levels. Currently, the most likely explanation is based on hydrodynamic effects related to the drainage film formed between two colliding bubbles [5]. Surface effects can arise because even though ions are repelled from the surface of water, due to an image charge repulsion, once the bulk salt concentration is sufficiently high, ions will be forced to reside at the surface. To reduce energy, they will most likely adsorb as ion pairs and this could set up a local electrostatic field at the surface, which could immobilize adjacent water layers. If this happens, it will induce a "zero slip" boundary condition at the surface, which will reduce the rate of film drainage between two approaching bubbles, and so, increase the likelihood of the bubbles separating before they can coalesce, especially within a turbulent bubble chamber. In addition, the observation that some salts inhibit coalescence and others do not [2,3] could then be explained in terms of their ability to create this local electrostatic field, as ions are forced into the surface region at high concentrations. Some salts will produce this immobilization, whereas others will not. This important problem remains the subject of investigation [4,5].

Whatever the cause of this effect, the high bubble densities found in salt solutions even with high gas inlet temperatures support the possibility that a novel water sterilization process could be developed using this process.

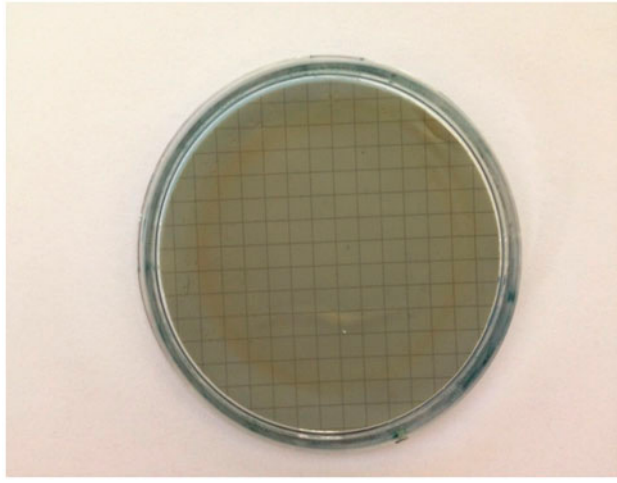

Fig. 5. Photograph of a 10 mL sample of distilled water sample following microfiltration, and 24 h of incubation (at 37˚C) with M-FC agar with rosolic acid. No colonies were observed.

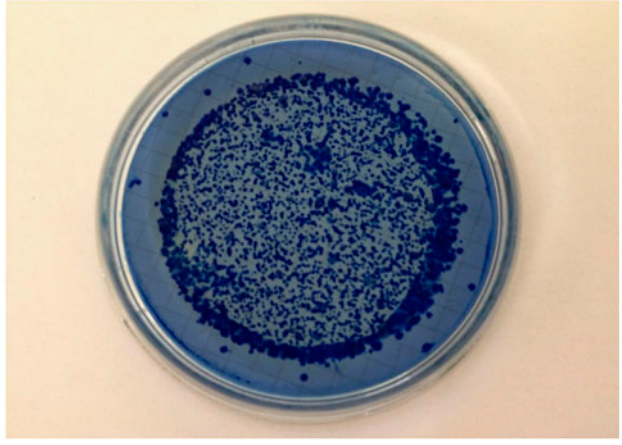

Fig. 6. Photograph of a 10 mL sample of a raw lake water sample (with added 0.15 M NaCl) following microfiltration, and 24 h of incubation (at 37˚C) with M-FC agar with rosolic acid. Numerous (blue) coliform colonies were observed.

The effects of gas inlet temperature, flow time, and residence time in the bubble column were studied with sterilization efficiency using the bubble column method. Fig. 5 shows an example of a "blank" distilled water result following incubation for 24 h with the growth media following the filtration procedure. No growing colonies are visible. By comparison, Fig. 6 shows the high density of fecal coliform colonies (blue) present in a 10 mL sample of the raw lake water. Diluting these samples 100 × produces counts of around 100 per plate, which corresponds to around 1,000 coliforms per mL for the raw lake water samples. The colonies were not affected by the level of added salt, as expected [16]. These high coliform counts were very useful for monitoring the sterilization of heavily contaminated waters in this study. Even higher levels of coliform numbers have been observed in natural lakes in the presence of high densities of waterfowl species [17]. Typical samples of the raw lake water used in this study gave turbidity values in the range of 35–40. Clearly, there were many other particles present in the raw lake water, as expected. However, in this study only fecal coliforms present in the lake water in large numbers were used to monitor thermal sterilization.

After only 2 min of bubbling 90˚C (dry) air through 200 mL samples of the raw lake water (with added 0.15 M NaCl) at a gas flow rate of 23 L/min (BOC gauge inlet gas flow rate), no colonies were detected just above the center of the glass sinter. These initial results indicated that even a short duration exposure to the relatively small, hot bubbles may cause heat sterilization of even heavily contaminated water samples. However, there may also have been a slight flotation effect, since the coliforms (typically 2–3 μm in size) are slightly hydrophobic [18,19]. Hence, these experiments were repeated collecting all of the 200 mL column solution, including the transient surface foam. In this case, many colonies were detected. It is possible that the removal of any detectable coliforms just above the sinter could be due to a combination of heat sterilization and flotation removal. It is important to understand that because of the rapid loss of heat expected, i.e. within a few tenths of a second [8] for these size bubbles, only a fairly thin layer of hot bubbles will be created at the sinter. Within about 1 cm (from the sinter), the bubbles will have cooled and will no longer be capable of thermal sterilization.

In order to estimate this rate of thermal equilibrium, a 5 cm high bubble column was set up with 0.15 M salt (alone) with a (room temperature) gas inlet flow rate of 23 L/min at a temperature of 150˚C. The temperature variations observed in the column are summarized in Table 1. These results clearly demonstrate that the hot inlet gas is indeed rapidly cooled by the water column. The earlier theoretical model, described by Eq. (1), predicts a steady state equilibrium column temperature of around 40˚C, as observed. In addition, even though the column solution was only 5 cm high, the bubbles were completely cooled. The temperature measured in the center of the column solution just above the sinter (see Table 1) remained close to the equilibrium temperature of the column and much lower than the inlet gas temperature throughout the runs. These observations support the view that the hot gas bubbles leaving the sinter rapidly cool and can only sterilize the water via collisions with dispersed coliforms close to the sinter.

These results led to an experimental protocol whereby in each case all of the column solution was mixed at the end of the run and a 10 mL sample taken for testing. In all experiments, at least three repeat measurements were carried out. A summary of the sterilization results is given in Table 2.

The results in Figs. 7 and 8 were obtained using this method following exposure of the column to an inlet gas temperature of 150˚C for 30 and 60 min. Clearly, the coliforms are almost completely destroyed (>99.99%) by the process, after bubbling of the hot gas for a period of between 30 and 60 min, even though the column solution temperature remained no higher than about 45˚C.

Table 3 summarizes the main differences between water sterilization using boiling and the low-tempera-

Table 1
Measured temperatures within a bubble column containing 200 mL of 0.15 M NaCl solution with an inlet air temperature of 150˚C and an (RT) air flow rate of 23 L/min

Time in minutes	Temp in the air just above water column/C	Column temperature at the sinter surface/C	Column temperature about 5–10 mm above the sinter/C
Just after pouring solution	40	35.8	30.8
2	43.6	44	40.4
5	46	47	44.6
10	47.3	48.2	47
15	46.9	47.5	47.5
20	46.2	47.1	47.6
25	46	46.9	47.7
30	46	46.9	47.8
35	46	46.9	47.7

Table 2
A summary of column sterilization experiments using the total column solution for coliform counting

Air inlet temp/C	Run time						
	2 min	15 min	20 min	30 min	40 min	60 min	70 min
80°	HFC	HFC	HFC	MFC	MFC	MFC	MFC
90°	HFC	HFC	HFC	MFC	MFC	MFC	LFC
100°	HFC	HFC	MFC	MFC	LFC	LFC	>99.99% sterilization
150°	HFC	MFC	LFC	LFC	LFC	>99.99% sterilization	>99.99% sterilization

Notes: HFC—high fecal coliform numbers. MFC—medium fecal coliform numbers. LFC—low fecal coliform numbers.

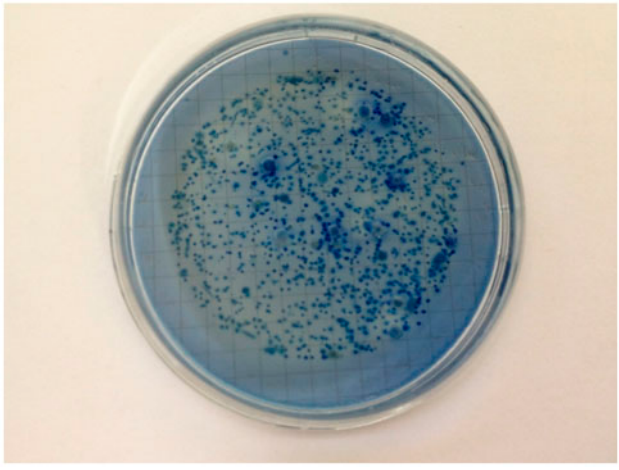

Fig. 7. Photograph of the (blue) coliform colonies obtained from raw lake water with added 0.15 M NaCl following treatment in the bubble column with an inlet gas temperature of 150˚C for 30 min. The entire column solution was collected and mixed and a 10 mL sample was passed through a microfilter and incubated for 24 h (at 37˚C) with M-FC agar with rosolic acid. A large number of (blue) coliform colonies were observed.

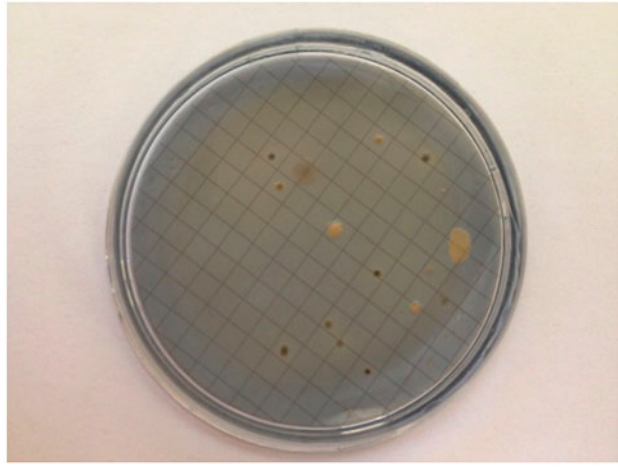

Fig. 8. Photograph of the incubated agar growth plate obtained from raw lake water with added 0.15 M NaCl following treatment in the bubble column with an inlet gas temperature of 150˚C for 60 min. The entire column solution was collected and mixed and a 10 mL sample was passed through a microfilter and incubated for 24 h (at 37˚C) with M-FC agar with rosolic acid. No (blue) coliform colonies were observed.

ture bubble column method. For example, continuous boiling can produce scale deposits in water high in calcium requiring regular cleaning. Also, the water sterilized with the bubble column method does not have to be cooled for further use. Probably, the main advantage of the bubble column method is the significantly reduced demand for thermal energy. The low temperature process also offers a safer method without potential exposure to boiling water. A sealed, inline gas heater also offers a safer heat supply system.

Since the coliforms should be unaffected by this solution temperature, the effects observed appear to have been caused by collisions between the hot gas bubbles and the coliform particles close to the sinter, where the gas bubbles are still hot enough. The gas leaving the top of the column was about 40˚C which shows that the flotation process did not contribute to the sterilization process, other than through a negative effect in partially excluding coliforms from the regions just above the sinter at the base of the column. The relatively long time taken to fully sterilize the entire solution of heavily contaminated water seems to be determined by the time required to allow all of the coliforms to be exposed to the hot gas bubbles just above the sinter. The coliforms collected in the transient foam at the top of the column could not have been sterilized there because of the low temperature of the gas leaving the top of the column.

These results suggest that a practical process will involve the continuous flow of contaminated water

Table 3
Comparison of water sterilization by boiling and using the bubble column method

S. No.	Sterilization with boiling	Bubble column sterilization
1	Irregular process which is hard to control resulting in energy wastage	Controlled, regular process
2	Produces fouling/scale formation	Self-cleaning method
3	Requires a considerable amount of energy[a]	Significantly lower thermal energy usage
4	Does not remove suspended or dissolved compounds[a]	Flotation helps to remove suspended and dissolved compounds
5	Potential for burn injuries[a]	Safe, low temperature method
6	Indoor pollution: increased risk of respiratory infections from indoor stoves or fires[a]	Reduced health risk by use of a sealed inline gas electrical heater
7	After boiling, water needs cooling down (cannot be consumed immediately)[a]	No need to cool

[a]Source: http://www.akvo.org/wiki/index.php/Boiling

into the top of a modest, 5–10 cm high, bubble column with the thermally sterilized water being continually taken from the hot gas bubble region just above the sinter. Although only 200 mL column solutions were used in many of these batch experiments, for convenience, much higher volumes could be treated using this type of continuous flow process. It should also be noted that the raw water samples used in this study were heavily contaminated with fecal coliforms, at a much higher level than most natural water samples.

Fig. 9 gives an example of the effect of bubble size on the efficiency of the process. Removal of the NaCl from the column solution leads to the production of much larger bubbles and this in turn reduces the degree of sterilization by the column process. These results were obtained at a gas flow rate of 23 L/min with a gas inlet temp of 150˚C for 60 min. It is likely that both the flotation effect and the heat transfer process will be substantially reduced once the salt is removed, as can be seen by comparison with the results presented in Fig. 8. These results also show that the heated sinter plate did not produce a significant contribution to the sterilization process, simply through contact with the coliforms, since the plate would have maintained a high temperature under both experimental conditions. However, even a visual comparison between the raw lake water sample (Fig. 6) and the salt-free water results indicates that the bubble sterilization process can also be effective for the treatment of drinking water. Sterilizing (salt-free) drinking water using this process should also become more efficient with the continuous flow method, discussed earlier, where the product water is taken from just above the sinter.

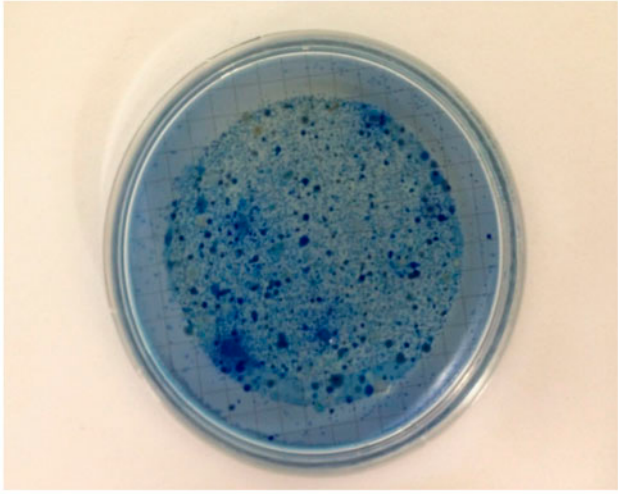

Fig. 9. Photograph of the incubated agar growth plate obtained from raw lake water without the addition of 0.15 M NaCl following treatment in the bubble column with an inlet gas temperature of 150˚C for 60 min. The entire column solution was collected and mixed and a 10 mL sample was passed through a microfilter and incubated for 24 h (at 37˚C) with M-FC agar with rosolic acid. Significant numbers of (blue) coliform colonies were observed.

It is interesting to compare the thermal energy cost to produce water sterilization by passing 23 L/min of air at 150˚C through a suitable bubble column for 60 min with simple boiling for, say, 1 L of water. The heat capacity (at a constant pressure, i.e. C_p) of nitrogen gas in units of J/Km^3 can be calculated from the fairly constant, with temperature, gas heat capacity per mole. At 150˚C, this corresponds to about 840 J/Km^3. For a flow rate of 23 L/min for 60 min, this corresponds to a required total heat to raise this volume of gas from 20 to 150˚C of about 150 kJ. By comparison, heating a litre of water from 20˚C to the boiling point requires about 340 kJ, this is the minimum heat, i.e. without any boiling. In practice, the commonly recommended method of boiling will substantially increase this amount because of the high latent heat of

vaporization of water. Assuming 5% evaporation during boiling would increase the energy demand to about 450 kJ. Even by comparing just the heat to raise water to the boiling point, the bubble column process clearly requires substantially less thermal energy. Although we have not studied the maximum volume that can be sterilized by the bubble column, the results of this study indicate that a higher capacity bubble column is likely to be just as effective. This would improve the efficiency of the sterilization process still further. Of course, less heavily contaminated water would also be easier to sterilize.

In the studies reported here, coliform counts were used as the sole indicator of degree of water sterilization. However, in future work this should be extended to include other waterborne micro-organisms such as Cryptosporidium, Giardia, and Enterobacter [20].

4. Conclusion

The new method for sub-boiling, thermal sterilization presented here is based on some of the unusual properties of water and salt solutions. These initial studies demonstrate that a bubble column produced using the combined effects of bubble coalescence prevention, due to the presence of salt, and the rapid transfer of heat from small, hot gas bubbles to the surrounding water can be used as an effective and energy efficient method of sterilizing contaminated water. This method uses a significantly lower amount of energy than the conventional method of boiling water. It is also a safer method because the water temperature never has to rise above about 50 °C. The heat is supplied to the waterborne biological contaminants directly, without heating the water. Commercially, waste low-quality heat and waste vent gases are widely available, at low cost and these could be used to sterilize large volumes of water for further applications.

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References

[1] V.I. Klassen, V.A. Mokrousov, An Introduction to the Theory of Flotation, Butterworths, London, 1963.
[2] V.S.J. Craig, B.W. Ninham, R.M. Pashley, Effect of electrolytes on bubble coalescence, Nature 364 (1993) 317–319.
[3] V.S.J. Craig, B.W. Ninham, R.M. Pashley, The effect of electrolytes on bubble coalescence in water, J. Phys. Chem. 97 (1993) 10192–10197.
[4] V.S.J. Craig, Bubble coalescence and specific-ion effects. COCIS 9 (2004) 178–184.
[5] S. Marcelja, Short-range forces in surface and bubble interaction, COCIS 9(1–2) (2004) 165–167.
[6] M.J. Francis, R.M. Pashley, Application of a bubble column for evaporative cooling and a simple procedure for determining the latent heat of vaporization of aqueous salt solutions, J. Phys. Chem. B 113 (2009) 9311–9315.
[7] CRC Handbook of Chemistry and Physics, 93rd Edition, (2012–2013), pp. 4–124.
[8] I. Leifer, R.K. Patro, P. Bowyer, A study on the temperature variation of rise velocity for large clean bubbles, J. Atmos. Ocean Technol. 17 (2000) 1392–1402.
[9] R. Clift, J.R. Grace, M.E. Weber, Bubbles Drops and Particles, Academic Press, New York, 1978.
[10] A. Bahram, B. Hamid, N. Akram, Estimation of coliform contamination rate and impact of environmental factor on bacterial quality of tube well water supplies in Khorramdarreh County, Iran. Afr. J. Biotechnol. 11 (2012) 7912–7915.
[11] E.E. Geldreich, H.F. Clark, C.B. Huff, L.C. Best, Fecal-Coliform-Organism Medium for the Membrane Filter Technique, JAWWA 57 (1965) 208–214.
[12] S.P. Frankel, K.J. Mysels, On the 'Dimpling' During the Approach of Two Surfaces, J. Phys. Chem. 66 (1962) 190–201.
[13] J.N. Israelachvili, Intermolecular and Surface Forces, Academic Press, London, 1992.
[14] J.N. Israelachvili, R.M. Pashley, The hydrophobic interaction is long-range, decaying exponentially with distance, Nature 300 (1982) 341–343.
[15] H.K. Christenson, P.M. Claesson, Direct measurements of the force between hydrophobic surfaces in water, Adv. Coll. Int. Sci. 91 (2001) 391–436.
[16] S.M. Abdulkarim, A.B. Fatimah, J.G. Anderson, Effect of salt concentrations on the growth of heat-stressed and unstressed *Escherichia coli*, J. Food Agric. Environ. 7 (2009) 51–54.
[17] J.A. Brierley, D.K. Brandvold, C.J. Popp, Waterfowl refuge effect on water quality: I. Bacterial populations, J. Water Pollut. Control Fed. 47 (1975) 1892–1900.
[18] R.M. Goulter, I.R. Gentle, G.A. Dykes, Issues in determining factors influencing bacterial attachment: A review using the attachment of *Escherichia coli* to abiotic surfaces as an example, Lett. Appl. Microbiol. 49 (2009) 1–7.
[19] S.S. Tazehkand, S. Torkzaban, S.A. Bradford, S.L. Walker, Cell prepartion methods influence *Escherichia coli* D21g surface chemistry and transport in saturated sand, J. Environ. Qual. 37 (2008) 2108–2115.
[20] K. Pond, Water Recreation and Disease, Plausibility of Associated Infections: Acute Effects, *Sequelae and Mortality*, World Health Organization (WHO), IWA Publishing, London, 2005.